UtahStateUniversity
BINGHAM RESEARCH CENTER

HYDROCARBON EMISSION DETECTION SURVEY OF UINTA BASIN OIL AND GAS WELLS

FINAL REPORT

Seth Lyman
Trang Tran
Marc Mansfield
Bingham Research Center
Utah State University
320 N Aggie Blvd
Vernal, UT 84078

Arvind Ravikumar
Department of Energy Resources Engineering
Stanford University
367 Panama St
Stanford, CA 94305

DOCUMENT NUMBER:	BRC_180908A
REVISION:	DRAFT FOR REVIEW
DATE:	08 SEPTEMBER 2018

Executive Summary

We used FLIR GF320 infrared leak detection cameras to detect hydrocarbon emissions from oil and natural gas wells in Utah's Uinta Basin. The purposes of this study were to (1) better understand the sources of hydrocarbons from the oil and gas industry and (2) investigate different emissions detection approaches. We surveyed 3,428 oil and gas facilities from a helicopter in February and March 2018, including well pads, compressor stations, and gas plants (though emissions were only observed from well pads). We also surveyed from the ground 419 of the same well pads that were part of the helicopter survey.

This study was funded by the Bureau of Land Management, the Utah Legislature, the Utah Division of Air Quality, and the U.S. Environmental Protection Agency. A steering committee consisting of representatives from the Ute Indian Tribe, the Bureau of Land Management, the Utah Division of Air Quality, and the U.S. Environmental Protection Agency worked with our research team to plan the study and guide its execution.

The study's major conclusions include:

- Cold temperatures dramatically reduce the detectable emission rate of infrared leak detection cameras, especially when cameras are used from an aerial platform. The aerial portion of this study detected less than 1/10th the number of emission plumes that were observed in a similar study performed during summer months and had a detection limit that was between 2.5 and 7 times worse.
- Ground-based infrared camera surveys are able to detect much smaller emissions than aerial surveys. During the ground survey, we detected emissions at 31% of well pads, compared to 0.5% of pads during the aerial survey, and the detection limit for our camera, when used from the ground, was at least 10 times better than when the camera was used from the helicopter.
- Well pads with detected emissions during the ground and aerial surveys had higher oil and gas production, were younger, and had more liquid storage tanks per pad relative to the entire surveyed population.
- The majority of observed emission plumes were from liquid storage tanks (75.9% of all observed plumes), including emissions from thief hatches, pressure relief valves, and tank piping.
- Well pads with emissions control devices on tanks were more likely to have detected emissions, had more detected emissions per pad, and were more likely to have emission plumes that were qualitatively categorized as large. Emissions from pads with tank controls originated mostly from tanks.
- Repairs made by oil and gas companies in response to emissions detected ranged from small maintenance and repair work that cost between zero and a few hundred dollars, to replacement of thief hatches that cost several thousand dollars. Most repairs reported cost well under $1,000.

Contents

List of Tables

List of Figures

1. Introduction

Optical gas imaging cameras visualize a narrow band of the infrared spectrum in which methane and other hydrocarbons are absorptive (between 3 and 4 µm, depending on the make and model of the camera), allowing users to visualize volatile hydrocarbon emission plumes that are invisible to the human eye. These cameras allow users to quickly and definitively locate natural gas leaks from oil and gas industry facilities and equipment. Use of these cameras within the oil and gas industry is widespread. New U.S. Environmental Protection Agency regulations require semi-annual leak detection and repair at most oil and gas wells constructed after June 2017 (CFR, 2016), and they allow operators to use optical gas imaging for this purpose. Government agencies also use optical gas imaging cameras for regulatory compliance inspections.

Scientific studies have shown the utility of optical gas imaging technology (Brantley et al., 2015; Lyon et al., 2016; Subramanian et al., 2015; Thoma et al., 2017) and have highlighted challenges to their use. This technology is qualitative, and the minimum detectable leak rate of optical gas imaging cameras is variable. Ultimately, the detectable leak rate depends on the amount of contrast in the camera image between the plume and the background behind the plume. Factors that influence contrast between the plume and the background include plume conditions (plume temperature, density and composition), the conditions of the background (surface temperature, reflectivity, and insolation), meteorology (which impacts both plume and background conditions), the distance of the camera from the emission source, camera settings, and on the operator's experience and visual acuity (Fox et al., 2017; Mansfield et al., 2017; Ravikumar and Brandt, 2017; Ravikumar et al., 2016; Ravikumar et al., 2018).

Two previous optical gas imaging surveys of emissions from oil and gas production facilities have been conducted in Utah's Uinta Basin. The first was a helicopter-based survey conducted during summer 2014 by Lyon et al. (2016). Lyon et al. surveyed 1389 well pads over nine days and detected emissions from 6.6% of surveyed pads. Relative to the entire surveyed population, pads with detected emissions were newer, higher producing and were more likely to be oil wells. Almost all of the emissions observed by Lyon et al. were from liquid storage tanks. The second previous survey was a ground-based survey conducted during the summer and fall 2016 by Mansfield et al. (2017). They surveyed 454 wells from the ground at the edge of well pads and detected emissions from 39% of pads surveyed. All of the wells surveyed by Mansfield et al. were oil wells, all were constructed within the previous few years, and all had control devices installed to reduce emissions from liquid storage tanks. As with the Lyon et al. study, the majority of observed emissions in Mansfield et al. study were from liquid storage tanks.

Here we present the results of simultaneous aerial and ground-based optical gas imaging surveys conducted in winter and spring 2018 using methods similar to Lyon et al. (2016) and Mansfield et al. (2017), respectively. We compare the results from aerial and ground-based survey platforms, make comparisons among all the surveys that have been conducted in the Uinta Basin, and investigate the impacts of meteorological and surface conditions, well pad properties, pad ownership, and other factors on the frequency and qualitative size of detected emissions.

2. Methods

2.1. Aerial survey

We contracted with Leak Surveys, Inc. to conduct the aerial survey in late February and early March 2018. They used a FLIR GF320 camera from a helicopter at about 75 m above ground to survey for leaks at 3,428 oil and gas facilities, including well pads, compressor stations, and gas processing plants. 652 of the pads surveyed were also surveyed by Lyon et al. (2016) (19% of the facilities in this study, 47% of the pads in the Lyon et al. study). Figure 2-1 shows a photograph of the survey helicopter above the location of a controlled propane release.

Prior to the survey, we designated 29 rectangular areas in which Leak Surveys, Inc. would survey for emissions. These areas encompassed 44% of all producing wells and 50% of compressor stations and gas plants in the Uinta Basin. They included facilities operated by 28 different oil and gas companies. The helicopter survey crew flew back and forth across each area and briefly inspected with the FLIR camera each facility they encountered. If they saw an emission plume, they circled the facility for 90 s while recording a video of the plume. They also recorded the latitude and longitude, sources of observed emission plumes, whether people were at the observed facility, and types of equipment at each location where emissions were observed. At every fifth location where emissions were observed, they circled the facility for 4 min while recording a video to investigate whether observed emissions were continuous or intermittent over that period.

Figure 2-1. Photograph of survey helicopter above a controlled propane release location.

2.2. Ground Survey

We used a FLIR GF320 camera to conduct the ground survey in February and early March 2018, as well in April and May 2018. During February and March, the ground survey crew operated in the same rectangular areas and on the same days as the aerial survey, though the ground survey crew visited fewer wells and fewer areas per day. The ground crew only surveyed oil and gas well pads (419 pads). They surveyed from the edge of the well pad. They used a tripod or the vehicle to stabilize the camera and spent several minutes at each well scanning for leaks, including in the camera's high-sensitivity mode. High sensitivity mode improves contrast and visualization of emission plumes, but it creates a grainy image. The aerial survey was not able to operate in high-sensitivity mode because of the difficulty of interpreting images in high-sensitivity mode while the helicopter was moving.

If the ground survey crew detected emissions from any source, they recorded a video of the emissions. They made a qualitative determination of whether the observed emission plume was small, medium, or large. They also recorded how many distinct emission sources they observed and the source of the emissions.

At every well they encountered, whether emissions were observed or not, the survey crew recorded their distance from the well as determined by a rangefinder. Meteorological instrumentation that measured temperature, humidity, barometric pressure, wind speed and direction, and solar radiation (April and May only for solar radiation) was mounted to the top of the survey crew's vehicle. Meteorological instrumentation used was calibrated against NIST-traceable standards within the prior 12 months. The crew recorded meteorological information from the measurement instrumentation, as well as whether it was sunny or not at their location (April and May only), and what type of background was behind the observed emission plume (or behind the tanks at the well pad, if no emission plume was observed; April and May only). They also recorded the total number of oil, condensate, and/or water tanks they observed.

2.3. Steering Committee

A steering committee consisting of representatives from the Ute Indian Tribe, the Bureau of Land Management, the Utah Division of Air Quality, and the U.S. Environmental Protection Agency worked with our research team to plan this study and guide its execution.

2.4. Industry Involvement

We provided oil and gas companies whose facilities were surveyed with survey results within about 24 hours of the survey, and we provided videos as soon as we were able. After we sent videos and other final survey information, we asked companies at whose facilities emissions were observed to review the information we provided, visit locations where emissions were observed and provide feedback to us about sources of the observed leaks and any repairs that were made as a result of the survey.

2.5. Controlled Propane Releases

To determine the emission rates that were detectable from the helicopter and the ground under different conditions, we released commercial-grade propane (~95% propane) at different emission rates from a 5 cm diameter vertical tube at about 2 m above ground. We measured the emission rate with a Fox model FT3 mass flow meter. All releases were carried out between 14:00 and 15:00 local time. During each release, we measured meteorological conditions with the same system mounted atop the ground survey crew's vehicle.

The ground survey crew viewed propane emissions at a distance of 50 m from the tube with the ground-based camera. The helicopter crew viewed propane emissions at 50 m above ground on the first release day, and at 75 m on subsequent days.

2.6. Detection Limit Modeling

We used the method of Ravikumar et al. (2016) (also see Ravikumar and Brandt (2017) and Ravikumar et al. (2018)) to model the relationship between apparent ground temperature and detection limits during the aerial survey and for the time period of the Lyon et al. (2016) study. The Ravikumar model uses measured meteorological conditions and surface properties to simulate radiance from the plume and the background. Plume composition, leak size distribution, and distance from the plume are taken into account in the model.

2.7. Data Access, Processing, and Analysis

We obtained oil and gas facility information from the Utah Division of Oil, Gas and Mining (UDOGM, 2018). The aerial survey crew only recorded survey locations when emissions were detected, so we followed the method of Lyon et al. (2016) to produce a dataset of all the wells within the survey area. We excluded wells that were not producing (using February 2018 production data) and we aggregated well information to the pad level since wells on multiple-well pads with shared equipment were counted as a single facility by the aerial survey crew.

In addition to the meteorological data collected for the ground survey, we used data from the Vernal airport to compare meteorological conditions during this study to those during the Lyon et al. (2016) survey, and for detection limit modeling. The Vernal airport is the only station in the Uinta Basin at which sky cover information is collected. We obtained Vernal airport data from the National Climatic Data Center (NCDC, 2018). We used the MODIS Terra 500 m snow cover dataset (MODIS, 2018) to determine average percent snow cover for each area on each day of the aerial survey. For days during which a survey area had less than 50% data coverage in the MODIS dataset, we assumed that (1) the snow cover on the missed day was the average of the days before and after, or (2) the daily rate of change in snow cover in that area was the same as other survey areas with similar percent snow cover.

Average values are shown as average ± 95% confidence interval.

We calculated two metrics to characterize the statistics of observed emissions during the ground survey. These were (1) the number of observed emission plumes per well pad, and (2) a "severity score," intended to convey the qualitative size of emissions as observed by the survey crew. For the severity score, we assigned a value of 1 for plumes categorized as small, 2 for medium, and 3 for large. An average value was calculated for each well pad at which at least one emission is observed.

2.7.1. Monte Carlo Analysis of Company Performance

We used Monte Carlo analysis to answer this question about the plumes per pad and severity score metrics: When a metric for any particular company was smaller or larger than the overall result, was that merely a chance occurrence, or can we take it as evidence of underperformance or outperformance in emission suppression by one company relative to the others? We applied the following p-test to identify statistically significant departures by individual companies from the overall metrics. The complete ground survey included 419 well pads. Assume that M of these belong to company X. Let m_C be the value of one of the metrics evaluated over these M well pads. Then we take a large number (10^6) of independent, random subsets of the N well pads, each subset containing M well pads. Let m_R represent the value of the same metric for the random subsets. Then let p be the fraction of the time that the m_R values are less than m_C. We interpret this p as the probability that a random selection of M well pads outperforms the M well pads belonging to company X. Therefore, p near zero and one, respectively, means that company X outperforms and underperforms the pack, respectively, in emission suppression. If we accept the traditional threshold of 95% confidence, then $p < 0.05$ represents statistically significant outperformance, while $p > 0.95$ implies statistically significant underperformance, while any p between 0.05 and 0.95 is not strong evidence either way. (But p values always need to be taken with a grain of salt. At the 95%-confidence level, there are 1-in-20 odds that we will misjudge any one company, and exactly 20 companies are represented in the study.)

3. Results

3.1. Controlled Propane Releases

Table 3-1 provides information about the propane releases we conducted. The qualitative detectability of the propane plume from the helicopter did not appear to be dependent on the emission rate. The 5.04 g s^{-1} plume was less visible than that 1.89 g s^{-1} plume, in spite of being more than twice as large, perhaps because of the difference in helicopter height or the difference in meteorological conditions. The emitted propane plumes were clearly detectable with the ground camera (at a distance of 50 m) for all of the propane releases, the lowest of which was 0.14 g s^{-1}, though qualitative detectability appeared to be better on 28 February and 1 March than on 26 February. Figure 3-1 and Figure 3-2 show still images from the propane release conducted on 1 March. All the propane release videos are available at https://usu.box.com/v/2018-USU-IRsurvey.

Table 3-1. Information about controlled propane releases conducted to determine detectable emission rates. Height indicates the approximate height above ground of the helicopter.

Date	Emission Rate (g s^{-1})	Temper-ature (°C)	Wind Speed (m s^{-1})	Snow Cover	Height (m)	Plume in Aerial Video
26 Feb 2018	1.89	5.7	0.7	~80%	50	Faint, consistent
28 Feb 2018	5.04	7.2	1.2	Patchy, ~70%	75	Faint, inconsistent
1 Mar 2018	3.49	5.5	1.1	Patchy, ~50%	75	Clear, consistent
1 Mar 2018	3.21	5.4	1.3	Patchy, ~50%		
1 Mar 2018	2.14	5.1	1.1	Patchy, ~50%		
1 Mar 2018	1.52	5.1	1.1	Patchy, ~50%		
1 Mar 2018	0.80	5.1	1.1	Patchy, ~50%		
1 Mar 2018	0.24	5.1	1.1	Patchy, ~50%		
1 Mar 2018	0.14	5.1	1.1	Patchy, ~50%		

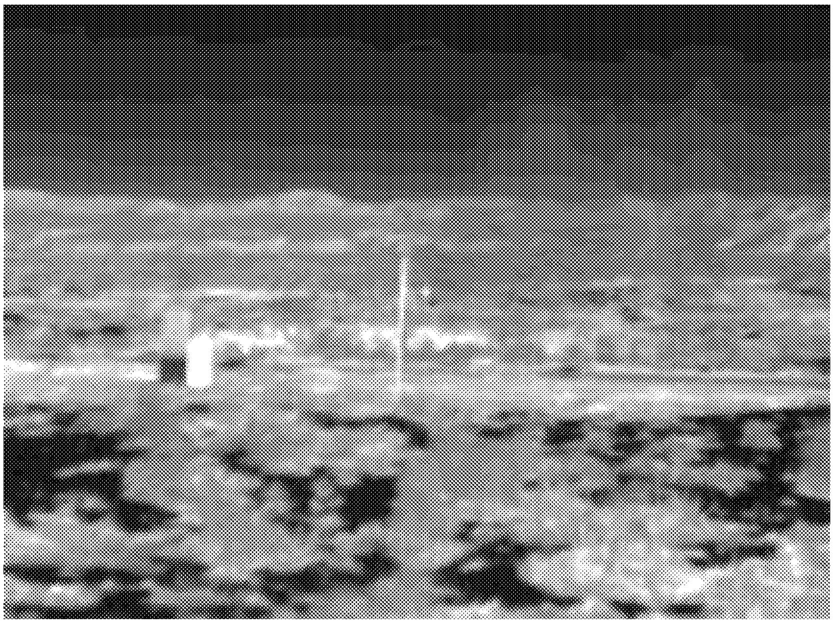

Figure 3-1. Infrared image taken from the ground on 1 March 2018 of propane being released from a tube during controlled propane release tests.

Figure 3-2. Infrared image taken from the helicopter on 1 March 2018 of propane being released from a tube during controlled propane release tests.

3.2. Survey Overview

Of the 3,428 oil and gas facilities in the aerial survey, emission plumes were only detected at 16 (0.5%), all of which were producing oil and gas well pads. Emissions were detectable at 129 of the 419 well pads visited during the ground survey campaign (31%). A total of 198 emission plumes, or 0.47 plumes per pad, were observed in the ground survey (some pads had none and others had multiple detected emission plumes).

Seven out of eleven companies responded to our request for information about survey results (Table 3-2 and Table 3-7). Of the four that did not respond, two had recently sold their assets in the Uinta Basin to another party, but the new ownership information was not available at the time of the survey. We received responses for 81% of the well pads at which we observed emissions in the aerial survey and 90% of the well pads at which we observed emissions in the ground survey.

Figure 3-3, Figure 3-4, and Figure 3-5 provide example still images from videos collected during the survey. The aerial and ground survey videos in these figures were from the same well pad, though the ground survey was conducted about two months after the aerial survey. The videos from which these still images were taken are available at https://usu.box.com/v/2018-USU-IRsurvey.

Figure 3-3. Infrared image taken from the helicopter at a well pad during the aerial survey.

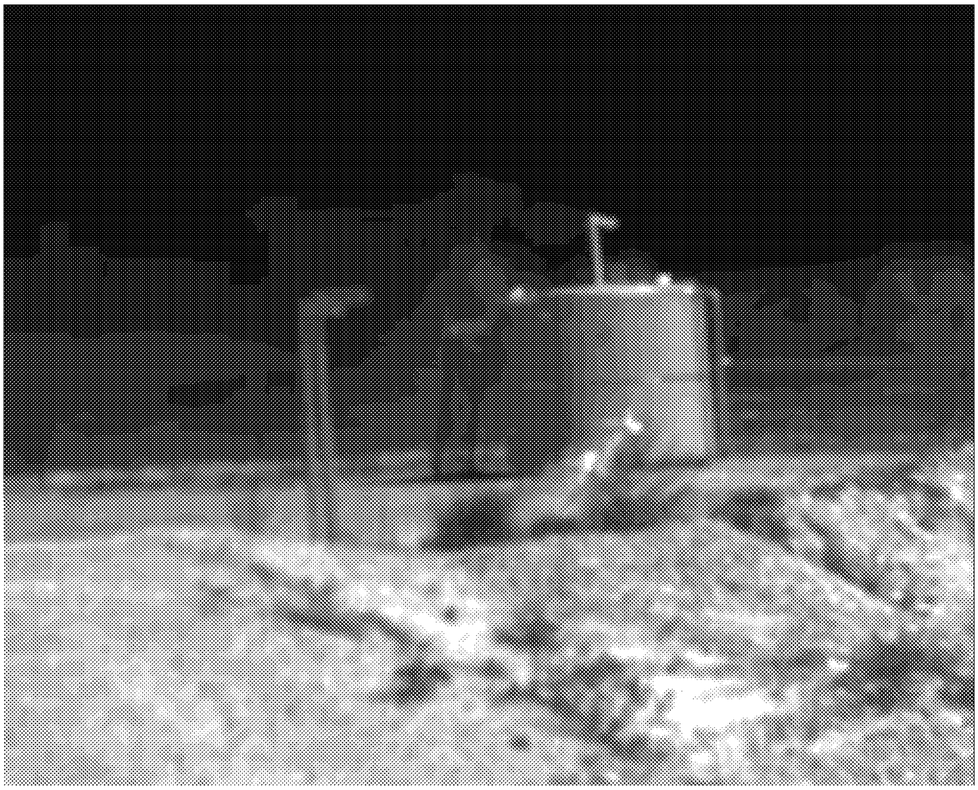

Figure 3-4. Infrared image taken from the ground at a well pad during the aerial survey. The emission source in this figure is the same as in Figure 3-3.

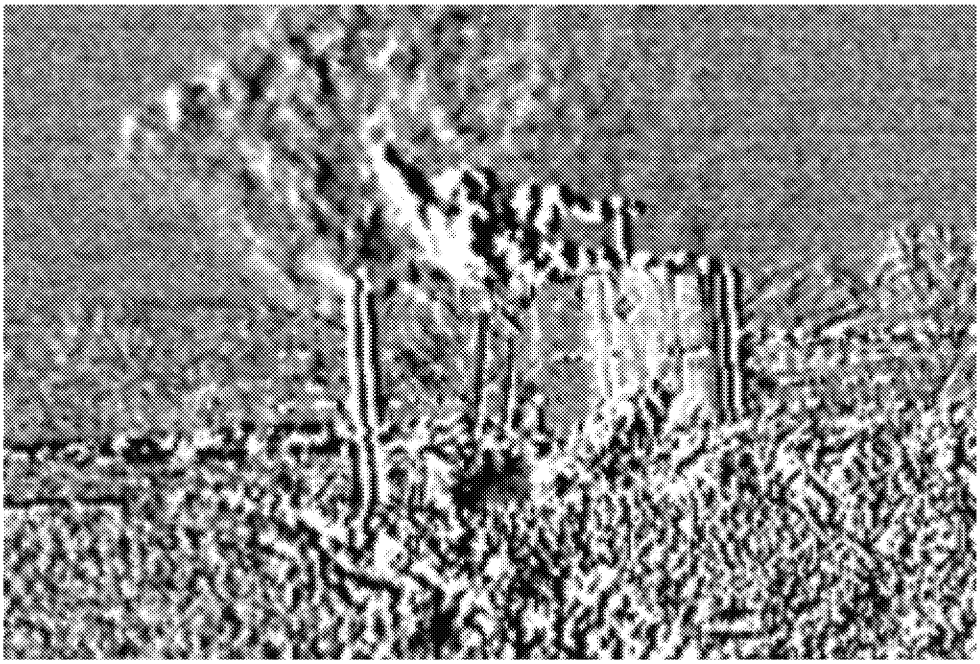

Figure 3-5. Infrared image taken in high sensitivity mode from the ground at a well pad during the aerial survey. This is an image of the same source shown in Figure 3-3 and Figure 3-4.

3.3. Meteorology

3.3.1. Aerial Survey

Average conditions were calm, cold, and clear during the aerial survey, with daytime wind speed of 1.4 ± 0.0 m s^{-1} (average ± 95% confidence interval of survey days), daytime temperature of -2.9 ± 2.3°C, and skies that were reported as clear for 92 ± 7% of daytime hours on survey days. Wind speeds ranged between 0 and 4.0 m s^{-1}. Daytime average temperatures varied between -9.1 and 2.6°C. Average hourly visibility was greater than 10 km on all survey days. Snow cover was 0.5 ± 0.6% in surveyed areas on survey days, and ranged between 0 and 8%. The number of emission plumes detected per pad on each aerial survey day was not correlated with daily meteorological conditions.

3.3.2. Ground Survey

The February and March portion of the ground survey was conducted on the same days as the aerial survey, so the conditions were identical for both surveys. During the April and May portion of the ground survey, wind speed at survey locations, temperature at survey locations, and percent of survey locations where it was reported to be sunny were 3.0 ± 0.2 m s^{-1}, 18.0 ± 0.7°C, and 70%, respectively. No snow cover existed during April and May.

We examined the impacts of ambient meteorological conditions (wind speed, temperature and cloudiness) and background conditions behind detected plumes or behind liquid storage tanks on emissions detected during the ground survey. Under calm to light breeze conditions (wind speeds between 0 and 3.5 m s^{-1}), emission detections were negatively and significantly correlated with wind speed (e.g., stronger wind tended to dilute plumes, making it less likely that the camera would detect a plume; $r^2 = 0.80$; $p < 0.01$), as was shown by Ravikumar and Brandt (2017). However, this correlation did not hold true when wind speed was above 3.5 m s^{-1} (Figure 3-6). Similarly, at a lower range of ambient temperatures (between 0 and 20°C), the percent of pads with detectable emissions increased as temperature increased ($r^2 = 0.63$; $p < 0.05$; Figure 3-7), as was shown by Ravikumar et al. (2016). Above this range, temperature did not seem to have an effect on emissions detection (Figure 8).

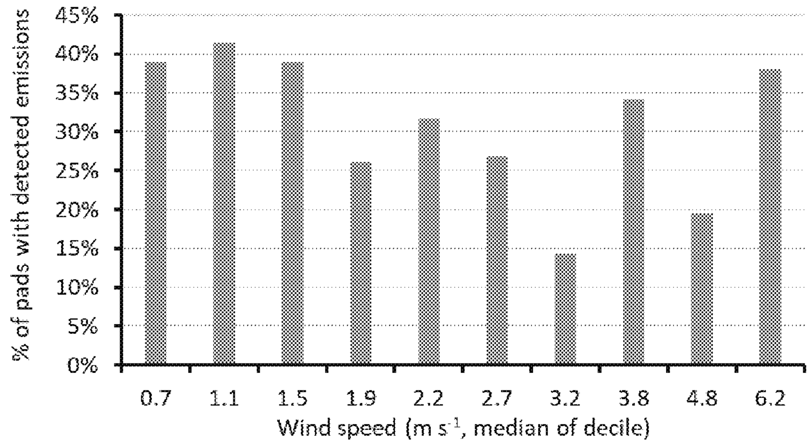

Figure 3-6. Percent of pads with detected emissions versus wind speed. The x-axis is organized by decile, and the median of each decile is shown.

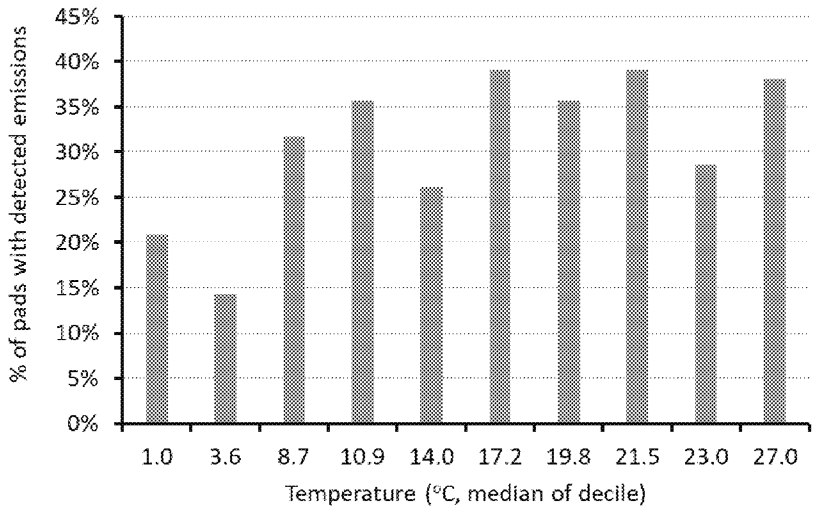

Figure 3-7. Percent of pads with detected emissions versus ambient temperature. The x-axis is organized by decile, and the median of each decile is shown.

Figure 3-8 shows that sunny conditions yielded more detected emissions than cloudy conditions. Sunny conditions allow for more surface heating, creating better contrast between the plume and the background if the ground is used as a background. Clear sky conditions also provide better contrast if the sky is used as a background (Ravikumar et al., 2016).

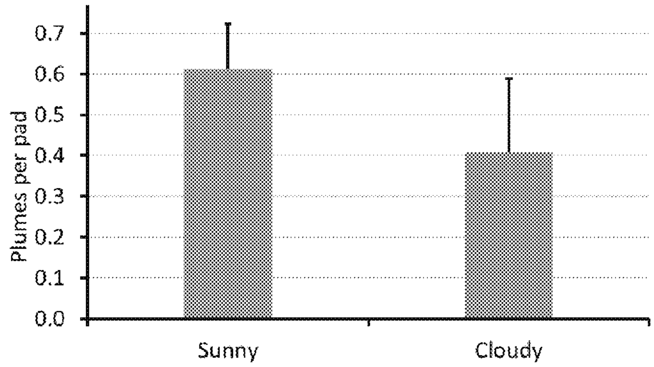

Figure 3-8. Impact of sunny or cloudy conditions on the number of emission plumes detected per well pad. This information was only collected in April and May. Tops of bars are averages, and whiskers represent 95% confidence intervals.

Four categories of background were reported by the ground survey crew: clouds, clear skies, ground (i.e., when looking down on the site from a higher location), and hillside (i.e., hills behind the well pad). Figure 3-9 shows that when the ground was used as background, fewer emission plumes were detected than when clouds or clear sky were used as a background, while a hillside background was associated with the highest detection rate among the four background types. However, these differences were not significant at the 95% confidence level. The ground and hillside background types had few surveyed pads (12 and 14 surveyed pads, respectively), leading to large confidence intervals.

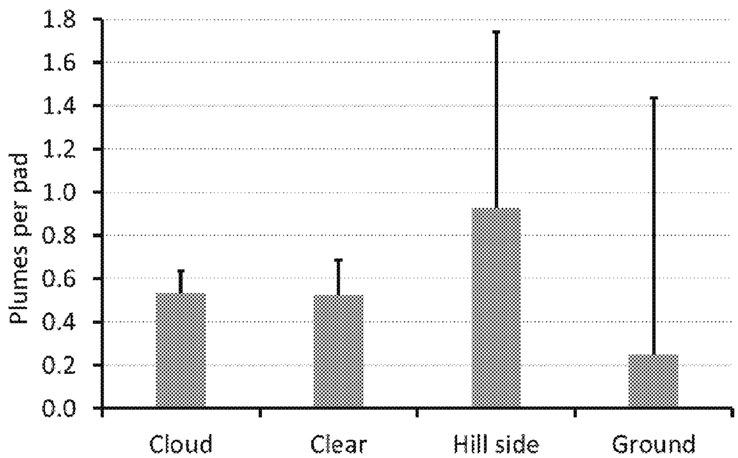

Figure 3-9. Impact of the background behind the plume (or behind tanks, if no plume was detected) on the number of emission plumes detected per well pad. This information was only collected in April and May. Tops of bars are averages, and whiskers represent 95% confidence intervals.

3.4. Sources of Observed Emissions

Sources of observed emissions were derived from notes made by the ground survey crew and responses received from companies. 65% of responses indicated that companies observed similar emissions to those found by our ground survey crew, while the other 35% either did not see any emissions in their subsequent inspection or did not see emissions from the same source(s). Two possible reasons exist for discrepancies between the ground survey crew's findings and the findings of companies in subsequent inspections: either (1) conditions at the pad changed between the two visits, leading to different emissions outcomes, or (2) one of the two parties was mistaken about the emission source. We assumed that (1) was the case, except when it was clear from information provided by companies that the ground survey crew's assessment was in error.

3.4.1. Aerial Survey

Table 3-2 presents details about each well pad at which emissions were detected for the aerial survey, including findings from the ground survey about two months later at the same well pads. The aerial surveys for the pads presented in Table 3-2 occurred between 28 February and 10 March, and the ground surveys occurred between 16 April and 10 May. The ground survey crew visited 15 of the 16 well pads at which emissions were detected from the helicopter. Where companies reported repairs, repairs were reported to have been made within two days of the aerial survey, and none of the repairs made involved any cost on the part of the operators.

Table 3-2 shows that all but one detected emission plume originated from liquid storage tanks. Repairs that were reported were routine tasks, including closing valves or hatches and making adjustments to control devices. At five of the pads, detected emissions were due to non-routine activities, including liquids unloading and activities related to a well workover. The ground survey crew detected emissions at 13 of 15 pads visited, including all the wells at which repairs were reported. Of the 11 pads at which detected emissions were not due to liquids unloading or non-routine maintenance, six showed the same source of emissions in both the aerial and ground surveys.

Table 3-2. Information about each well pad at which emissions were detected in the aerial survey. Leak size is a qualitative determination made by the camera operator.

			Aerial Survey				Ground Survey		
Com-pany	Pad Type	Tank controls	# plumes	Size	Emission source	Repairs made	# plumes	Size	Emission source
E	Oil	Yes	1	S	Tank vent line	Closed manual valve	1	S	Malfunctioning combustor
E	Oil	Yes	1	S	Tank vent	Closed manual valve	2	L, M	Tank vents
B	Oil	Yes	1	S	Thief hatch	None	1	L	Thief hatch
B	Oil	Yes	1	M	Tank vent—maintenance rig on location	None	None		
B	Oil	Yes	1	L	Tank vent	Adjusted flare regulator pressure	1	L	Tank vent (pressure relief valve)
B	Oil	Yes	2		Tank vent and thief hatch	None	4	L, L, L, L	Tank vents and surface piping
B	Oil	Yes	1	L	Tank vent	Relit combustor flame	1	L	Tank vent (pressure relief valve)
B	Oil	Yes	1	L	Tank venting after workover before connection to sales line	None	1	L	Thief hatch
L	Oil	No	2	S, M	Thief hatches	No operator response	2	S	Tank vents
L	Oil	Yes	1		Thief hatch	No operator response	2	L	Uncertain
H	Gas	Yes	1		Thief hatch during liquids unloading	None	Not surveyed		
H	Gas	No	1		Thief hatch during liquids unloading	None	None		
F	Oil	No	1	S	Burner exhaust on separator	None	2	M, S	Tank vent (pressure relief valve), uncertain
J	Oil	Yes	1		Thief hatch	Latched thief hatch	1	M	Uncertain
K	Gas	No	1		Tank vent	Closed manual valve	1	S	Tank vent
K	Gas	No	2		Tank vents during liquids unloading	None	2	S, S	Tank vents

3.4.2. Ground Survey

We performed statistical analyses with the entire ground survey dataset and on a sub-dataset that only included well pads equipped with emission controls on liquid storage tanks. Only pads with tank controls were surveyed in the STEPP study (Mansfield et al., 2017), and we include STEPP survey results for comparison where appropriate. Pads with controlled tanks were identified based on the 2014 Utah air agencies oil and gas emissions inventory (UDAQ, 2018), information received from well pad operators, and the ground survey crew's notes. Among the 419 surveyed well pads, we were able to identify 133 pads with controlled tanks. The actual number of well pads with controlled tanks could be higher than 133 because pads newer than 2014 are not included in the 2014 inventory, and because the survey crew only made notes about tank emission controls during April and May.

Among the 133 pads with controlled tanks, a total of 96 emission plumes were detected at 60 pads (45% of the visited pads), and 0.72 plumes per pad were observed, which was higher than the values for the entire dataset (31% of pads had detected emissions, 0.47 plumes/pad), and also higher than was reported in the STEPP study (39% of visited pads had detected emissions, 0.43 plumes/pad).

Table 3-3 shows emission sources at the 129 well pads where emission plumes were detected. For the entire dataset, thief hatches, pressure relief valves and tank vent pipes comprised the majority of emission sources (75.9% of all observed plumes), with emissions detected of all three qualitative sizes. Pads with emission controls on tanks had a similar emissions distribution to the entire dataset. The majority of the large plumes detected were located at well pads with controlled tanks.

These same source categories also made up the majority of detected emissions in the STEPP study. More emission plumes (mostly small) were detected from tank vent pipes in this study than in STEPP, and unidentified sources in this study were only 3%, compared with 8.7% in STEPP. This could be due to the ground survey crew having more experience in this study relative to STEPP (the same operators conducted the survey in both studies). It could also be due to differences in the cameras used (an Opgal EyeCGas was used in STEPP). Dehydrators were important emission sources in this study, but emissions from dehydrators were not reported in STEPP. In this study, the ground survey crew detected emissions from well heads and an underground pipeline, sources which were also not observed in the STEPP study.

Table 3-3. Sources and qualitative sizes of observed emissions for the entire dataset, well pads with controlled tanks, and for the STEPP study, which only included pads with controlled tanks.

	Entire dataset					Pads with controlled tanks					STEPP study				
	S	**M**	**L**	**TOTAL**	**%**	**S**	**M**	**L**	**TOTAL**	**%**	**S**	**M**	**L**	**TOTAL**	**%**
Thief hatch	19	27	13	59	30.3%	3	11	11	25	26.6%	8	41	44	93	47.4%
Pressure relief valve	24	18	13	55	28.2%	13	9	10	32	34.0%	19	19	15	53	27.0%
Tank vent pipe	18	7	9	34	17.4%	4	5	8	17	18.1%	0	7	5	12	6.1%
Methanol tank	0	0	0	0	0.0%	0	0	0	0	0.0%	6	0	0	6	3.1%
Other valve	0	0	0	0	0.0%	0	0	0	0	0.0%	3	3	0	6	3.1%
Combustor	3	1	2	6	3.1%	3	1	2	6	6.4%	1	2	0	3	1.5%
Pressure relief piping	0	0	0	0	0.0%	0	0	0	0	0.0%	2	0	1	3	1.5%
Flare stack	1	5	1	7	3.6%	0	2	1	3	3.2%	0	0	1	1	0.5%
Possible hole in tank	0	0	0	0	0.0%	0	0	0	0	0.0%	0	1	0	1	0.5%
Shack on site	0	0	0	0	0.0%	0	0	0	0	0.0%	1	0	0	1	0.5%
Unidentified source	2	2	0	4	2.1%	1	2	0	3	3.2%	6	1	10	17	8.7%
Underground pipe	0	1	0	1	0.5%	0	0	0	0	0.0%	--	--	--	--	--
Dehydrator	4	13	3	20	10.3%	1	3	2	6	6.4%	--	--	--	--	--
Chemical pump	0	1	0	1	0.5%	0	0	0	0	0.0%	--	--	--	--	--
Well head	4	1	3	9	4.6%	2	0	0	2	2.1%	--	--	--	--	--
TOTAL	75	76	44	195	100.0%	27	33	34	94	100.0%	46	74	76	196	100.0%

3.5. Well Pad Properties

Table 3-4 shows a comparison of the properties of all surveyed producing well pads and the pads at which emissions were detected. Compared to the entire population of surveyed pads, pads with detected emissions were higher-producing, were younger, and had more tanks per pad.

Table 3-4. Comparison of properties of well pads at which emissions were detected versus the entire surveyed population. (a) indicates data taken from the 2014 Utah air agencies oil and gas emissions inventory (UDAQ, 2018). Wells constructed after 2014 are excluded from these analyses.

	Aerial survey		Ground survey	
Well Pad Property	**Entire Population**	**Emissions Detected**	**Entire Population**	**Emissions Detected**
% that were oil wells	41.6%	75.0%	63.7%	62.8%
Avg. oil production (bbl day^{-1})	6.7 ± 0.7	41.2 ± 29.4	12.3 ±3.6	18.2 ± 6.5
Avg. gas production (MCF day^{-1})	100.1 ± 8.1	162.3 ± 93.9	84.2 ± 27.6	94.3 ± 50.0
Avg. pad age (months)	159 ± 4	107 ± 67	153.6 ± 12.7	141.6 ± 23.1
Avg. wells per pad	1.4 ± 0.0	1.6 ± .6	1.3 ± 0.1	1.3 ± 0.2
% with glycol dehydrators[a]	14.2%	22.2%	26.5%	14.3%
% with emission controls on tanks[a]	13.3%	55.6%	26.5%	40.0%
Avg. number of tanks per pad[a]	2.6 ± 0.1	4.7 ± 4.6	2.7 ± 0.2	3.4 ± 0.4

Many of the properties associated with an increase in detectable emissions were correlated. In the population of wells included in the aerial survey, per-pad production of barrels of oil equivalent (bbl day^{-1} of oil + MCF day^{-1} of gas / 5.8) was negatively correlated with pad age ($r^2 = 0.21$; $p = 0.04$) when production was binned by pad age at 24-month intervals. When binned in the same way, being an oil well pad (oil well pads were given a value of 1 and gas well pads a value of 0) was also negatively correlated with pad age ($r^2 = 0.15$; $p = 0.08$), probably because recent commodity prices have made oil production more cost-competitive than gas production. Younger, higher-producing pads may have more detectable emissions because equipment, including liquid storage tanks, is subject to higher throughput and higher pressures at these pads relative to lower-producing pads. The number of emission plumes detected per pad in the surveyed dataset was not significantly correlated with pad age ($r^2 = 0.12$; $p = 0.12$), but was correlated with production of barrels of oil equivalent ($r^2 = 0.75$; $p < 0.01$) and with being an oil well pad ($r^2 = 0.26$; $p = 0.02$).

Pads with emissions controls on liquid storage tanks were more likely to have emissions that were detectable from the helicopter. Having tank emissions controls was correlated with production of barrels of oil equivalent in the same binned dataset ($r^2 = 0.39$; $p < 0.01$). Also, the 2016 STEPP ground-based survey that only included wells with tank emissions controls showed that 39% of the wells surveyed had detectable emissions and that 82% of detected emissions were from tanks and infrastructure connected to tanks (Mansfield et al., 2017). (Brantley et al., 2015) came to a similar conclusion for well pads at which they measured emissions throughout the Rocky Mountain region. Tanks with emissions controls often leak, leading to detectable emission plumes.

The ground survey results showed similar trends, with pads at which emissions were detected being younger, with higher oil and gas production, more tanks per pad, and more likely to have tank emissions controls. The differences between the entire surveyed population and the pads with detected emissions were smaller in the ground survey than in the aerial survey, however. We expect that this was due to the large difference in the minimum detectable leak rates between the aerial and ground surveys. Only very large emission plumes were detectable in the aerial survey, so differences between pads with detectable plumes and all surveyed pads were more pronounced.

3.6. Qualitative Plume Size

Table 3-5 shows the prevalence of qualitative size classes of emission plumes detected in the ground survey and during the STEPP study (Mansfield et al., 2017). In the whole dataset, most emissions were categorized as small or medium, but for well pads with emissions controls on tanks, medium and large plumes were more common, and the percentages were similar to what was found in the STEPP study. This could be caused by the fact that pads with controlled tanks are more likely to have high oil and gas production, so emissions from tanks tend to be larger when they do occur.

Table 3-5. Prevalence of plumes of different qualitative size categories in the entire ground survey dataset, for well pads with controlled tanks, and for the STEPP study (which only included pads with controlled tanks).

Plume size	Entire dataset		Pads with controlled tanks		STEPP study	
Small	75	38%	27	28%	46	23%
Medium	77	39%	34	36%	74	38%
Large	44	22%	34	36%	76	39%
TOTAL	196	100%	95	100%	196	100%

Table 3-6 demonstrates a relationship between the ability to perceive a plume and the observation distance. We performed this analysis on the whole dataset only because the existence of controlled tanks does not affect the tested relationship. Similar to findings from the STEPP study, the fraction of well pads with no observable emissions increased from about 40% to almost 70% as the observation distance increased, and the fraction of small and medium plumes decreased. All plumes detected at distances over 103 m were in the large-size class. Distance from the emission source has been shown in other studies to be inversely related to detection limits (Ravikumar et al., 2016).

Table 3-6. Relationship between observation distance and qualitative size of plumes for the ground survey dataset. N, S, M, L are no detectable emissions, small, medium and large emissions, respectively.

Distance range	Pads of each size (N,S,M,L)	Percentage (N,S,M,L)
less than 16 m	7, 6, 1, 3	41%, 35%, 6%, 18%
16 to 34 m	45, 15, 28, 10	46%, 15%, 29%, 10%
34 to 57 m	120, 31, 20, 11	66%, 17%, 11%, 6%
57 to 80 m	77, 20, 18, 11	61%, 16%, 14%, 9%
80 to 103 m	32, 3, 10, 7	62%, 6%, 19%, 13%
103 to 126 m	6, 0, 0, 1	86%, 0%, 0%, 14%
over 126 m	2, 0, 0, 1	67%, 0%, 0%, 33%

For the entire dataset, oil well pads with qualitatively large plumes had more oil production than well pads with other size classifications (Figure 3-10). This same correlation was seen in a subset of oil well pads with emissions controls on tanks. This trend was slightly different from the STEPP study, in which pads with highest oil production were associated with both medium plumes and large plumes. In contrast, gas well pads with no detected emissions had higher gas production than pads with small, medium and large emission plumes (Figure 3-11).

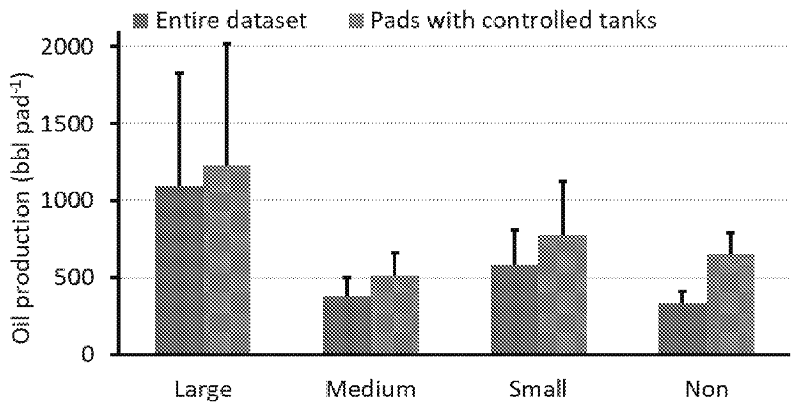

Figure 3-10. February 2018 oil production versus qualitative emission plume size, for the entire dataset and for pads with controlled tanks. Non indicates no detected emissions. Whiskers represent 90% confidence intervals.

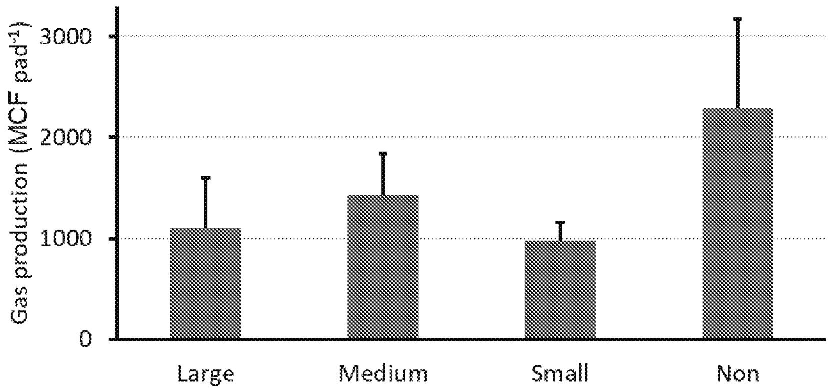

Figure 3-11. February 2018 natural gas production versus qualitative emission plume size. Non indicates no detected emissions. Whiskers represent 90% confidence intervals.

3.7. Results by Company

Table 3-7 and Table 3-8 provide company-level information about the results of the aerial and ground surveys. The company with the highest percentage of pads in the aerial survey with detectable emissions (company B) had the fifth-highest detectable emissions in the ground survey, and several companies with no detectable emissions in the aerial survey had a detection rate of 20% or more in the ground survey (Table 3-7). These discrepancies were likely caused by the different detection limits and population sizes of the two surveys.

Table 3-7. Aerial and ground survey results, organized by company. Total pads is the number of pads surveyed, and detects is the number of surveyed pads at which at least one emission plume was detected. Response received indicates whether the company responded to our request for information about observed emissions.

	Aerial survey			Ground survey				
Company ID	**Total pads**	**Detects**	**Percent detects**	**Total pads**	**Detects**	**Percent detects**	**% Oil wells in survey**	**Response received?**
A	16	0	0.0%	16	8	50%	81%	No
B	121	6	5.0%	64	19	30%	95%	Yes
C	58	0	0.0%	0			47%	N/A
D	21	0	0.0%	13	3	23%	100%	No
E	227	2	0.9%	58	28	48%	71%	Yes
F	474	1	0.2%	111	21	19%	71%	Yes
G	581	0	0.0%	85	36	42%	19%	Yes
H	755	2	0.3%	30	6	20%	30%	Yes
I	7	0	0.0%	4	1	25%	100%	No
J	65	1	1.5%	1	1	100%	91%	Yes
K	248	2	0.8%	35	5	14%	2%	Yes
L	75	2	2.7%	2	1	50%	69%	No
M	257	0	0.0%	0			23%	N/A
N	1	0	0.0%	0			0%	N/A
O	24	0	0.0%	0			0%	N/A
P	273	0	0.0%	0			69%	N/A
Q	2	0	0.0%	0			100%	N/A
R	1	0	0.0%	0			100%	N/A
S	13	0	0.0%	0			8%	N/A
T	6	0	0.0%	0			0%	N/A
TOTALS	**3225**	**16**	**0.5%**	**419**	**129**	**31%**	**42%**	**7 out of 11**

The frequency and qualitative size of detected emission plumes varied widely among companies whose well pads were surveyed in this study (Table 3-8). For the entire dataset, company B was statistically significantly associated with larger emission plumes than other companies, and companies E and G had significantly higher numbers of plumes detected per pad. For several companies (B, E, G, and H), the frequency and severity of detected emissions were higher for the subset of wells with tank emissions controls. Severity scores tended to be similar across this study and STEPP, except for company F, which had a much lower severity score in this study. The number of plumes detected per pad was higher for three out of five companies in this study compared to STEPP. This could be due to the increased number of detected plumes that were categorized as small in this study relative to STEPP (Table 3-5). Company K had the lowest number of plumes per pad and the lowest severity score. Company F, which had the largest number of surveyed pads in this study, also had significantly lower values for both metrics and had much lower values than during the STEPP study.

All operators that responded to the survey reported that they had a leak detection and repair program for wells in the Uinta Basin, though some reported that not all of their wells were covered by the program (Table 3-8). Of the companies that reported an inspection frequency, two reported that they conducted semiannual inspections, one reported annual inspections, and one reported that some of their wells were inspected annually, while others were inspected monthly. No clear relationship existed between inspection frequency and emission frequency or severity in Table 3-8.

Pads with emissions controls on tanks had a higher number of detected plumes per pad and a worse severity score than the entire dataset, and this difference was statistically significant (see the last row of Table 3-8). This is similar to the findings demonstrated in Table 3-3, Table 3-4, and Table 3-5, and together these findings show that wells pads with emission controls on tanks are more likely to (1) have detectable emissions from tanks and (2) have qualitatively larger emission plumes than the dataset as a whole.

Table 3-8. Average frequency and qualitative severity of detected emission plumes by company. **Values in blue indicate that the company's performance for a given metric is better than the group, as determined by a Monte Carlo analysis of statistical significance, and values in red indicate that a company underperformed the group.** LDAR frequency is also shown and indicates the frequency at which companies reported they inspect for leaks at the well pads in the survey.

		Entire dataset		Pads with controlled tanks		STEPP study	
Company	**LDAR frequency**	**Plumes per pad**	**Severity score**	**Plumes per pad**	**Severity score**	**Plumes per pad**	**Severity score**
A	--	0.63	2.5	0.83	2.4	0.27	2.2
B	Semiannual/none	0.41	2.2	0.44	2.4	0.36	2.4
C	--	--	--	--	--	0.36	2.2
D	--	0.31	2.3	0.36	2.3	0.38	2.6
E	None	0.91	1.9	1.47	2	0.55	1.8
F	Semiannual	0.3	1.6	0.13	1	0.6	2.2
G	Annual	0.66	1.7	1.43	1.8	--	--
H	Annual/monthly	0.2	2	0.25	2.3	--	--
I	--	0.25	2	0.33	2	--	--
J	Semiannual	1	2	1	2	--	--
K	--	0.17	1	0	0	--	--
L	--	1	1	1	1	--	--
Average		0.47	1.8	0.72	1.9	0.4	2.2

3.8. Reported Repairs

Companies reported that they made repairs in response to this study at 56 well pads (43% of all pads with observed emissions). At 34% of the pads for which we received responses, companies indicated that observed emissions from tanks were part of normal operations, and thus repairs were not needed. Repairs were completed within 43 ± 9 days of the ground survey date. Table 3-9 shows repair categories, the number of repairs made, and costs incurred for repairs.

Table 3-9. Number and cost of repairs reported by operators.

Repair category	Number of repairs made	Cost of repairs
Hatch maintenance	26	\$308 ± 122
Piping repair	8	\$127 ± 116
Combustor maintenance	7	\$119 ± 130
Pressure relief valve repair	7	--
Hatch replacement	6	\$3,872 ± \$1,630
Regulator replacement	1	--

3.9. Comparison of Regulatory Jurisdictions

The majority of the Uinta Basin is Indian country, which includes the Uintah and Ouray Indian Reservation and other lands for which the Ute Indian Tribe and the U.S. Environmental Protection Agency have regulatory authority for air quality. The state of Utah has regulatory authority for air quality on land that does not fall within Indian country. Table 3-10 shows the survey results and well pad properties for Indian country and lands under state jurisdiction for air quality.

Table 3-10 shows that emissions were four times more likely to be detected at well pads under state air quality jurisdiction during the aerial survey. In contrast, emissions were slightly more likely to be detected at pads in Indian country during the ground survey. As mentioned in the previous section, the detection limit for the aerial survey was much higher than for the ground survey, so only very large emission plumes were detected. Pads on state jurisdiction were more likely to be oil wells, had higher production, and were younger (in the aerial survey), all characteristics associated with a greater likelihood of having detectable emissions. For the ground survey, the much lower detection limit meant that emissions from low-producing and high-producing wells were both detectable, and the differences in well properties across regulatory jurisdictions were less important.

Table 3-10. Comparison of survey results and pad properties for different areas of jurisdiction for air quality regulations in the Uinta Basin. Data are for all surveyed pads unless otherwise indicated. (a) indicates data taken from the 2014 Utah air agencies oil and gas emissions inventory (UDAQ, 2018). Wells constructed after 2014 are excluded from these analyses.

	Aerial Survey		Ground Survey	
	State of Utah	**Indian Country**	**State of Utah**	**Indian Country**
% of all surveyed pads	17.7%	82.3%	43.7%	56.3%
Percent of pads with detects	1.2%	0.3%	26.2%	31.8%
% that were oil wells	99.5%	29.1%	98.9%	36.4%
Avg. oil production (bbl day^{-1})	18.3 ± 3.2	4.2 ± 0.5	20.7 ± 5.5	5.8 ± 4.8
Avg. gas production (MCF day^{-1})	56.3 ± 18.8	109.7 ± 19.3	86.0 ± 41.8	82.9 ± 36.8
Avg. pad age (months)	112 ± 9	169 ± 10	157.2 ± 19.3	150.7 ± 17.0
Avg. wells per pad	1.1 ± 0.0	1.5 ± 0.0	1.1 ± 0.1	1.4 ± 0.1
% with glycol dehydrators[a]	0.0%	15.3%	0.0%	46.7%
% with tank emission controls[a]	44.6%	10.9%	50.9%	8.0%
Avg. number of tanks per pad[a]	3.3 ± 0.1	2.6 ± 0.2	3.4 ± 0.3	2.3 ± 0.3

3.10. Comparison of Aerial Survey Results with Lyon et al. Study

Emission plumes were detected at a much lower percentage of oil and gas facilities in the current study relative to the Uinta Basin portion of the study performed by (Lyon et al., 2016) (Figure 3-12). The surveyed well pad population in this study was older, produced less oil, and produced a lower percentage of its energy from oil (determined using the method presented by (Lyon et al., 2016)) relative to the survey conducted by Lyon et al., all properties associated with a decreased likelihood of emissions that were detectable from the helicopter.

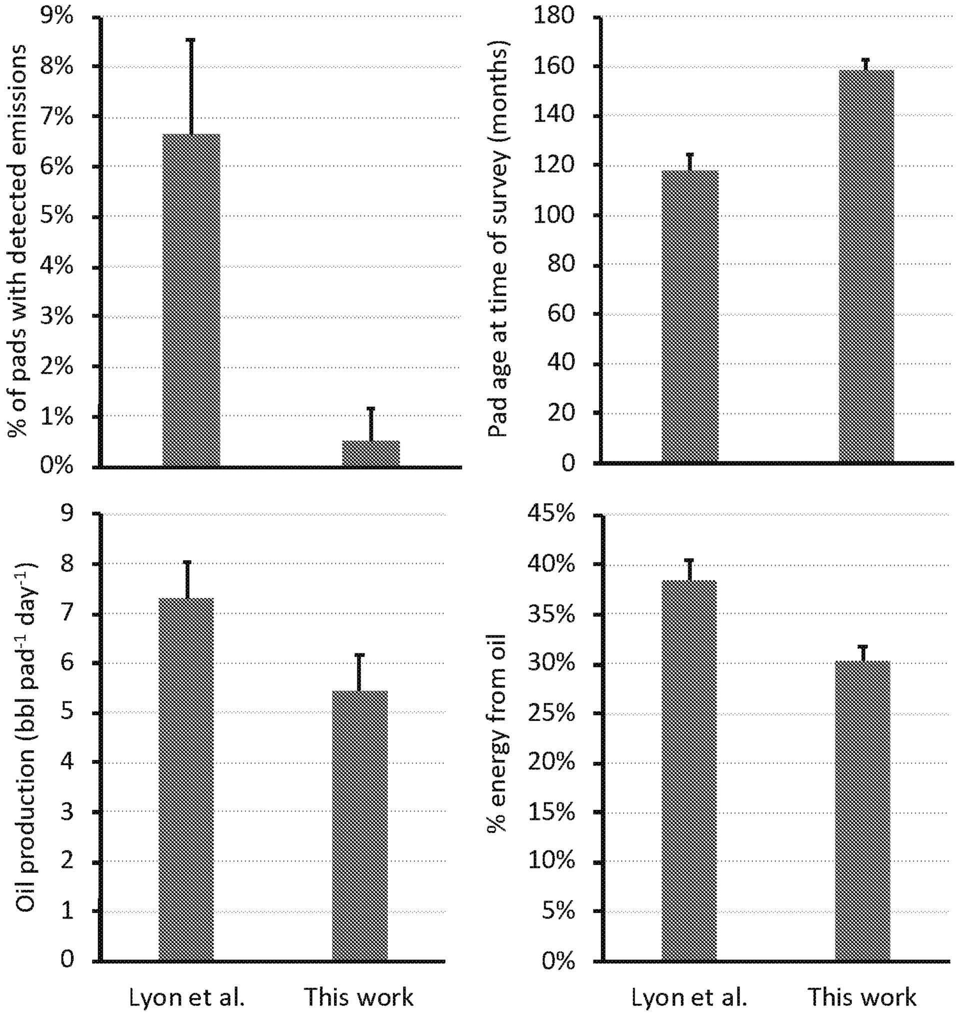

Figure 3-12. Comparison of well pad properties from the (Lyon et al., 2016) with this study. The panels show (clockwise from top left) percent of pads surveyed with emissions detected from the helicopter, age of all surveyed pads, oil production of surveyed pads, and percent energy from oil of surveyed pads. Top of bars are averages, and whiskers represent 95% confidence intervals. Confidence intervals for percent of pads with detected emissions are derived from daily values.

Englander et al. (2018) returned to the Bakken oil field in North Dakota and conducted an aerial infrared camera survey one year after the survey conducted by Lyon et al. (2016). Both surveys were conducted in September. For pads that were surveyed in both years, Englander et al. found a similar percentage of detected leaks (11.1% versus 10.8%). Further, they showed that pads with detected emissions in the first study were likely to be emitting in the second study. We, on the other hand, did not detect emissions at any of the 652 pads in our survey that were also part of the Lyon et al. survey, even though Lyon et al. detected emissions at 47 (7%) of those pads. Unlike the Englander et al. study, our study occurred four years after the original Lyon et al. study, allowing for significant changes in the industry to occur (e.g., Figure 3-12), and in a different season, resulting in poorer detection limits (see discussion below).

Wind speed and cloudiness were similar during this study and the Uinta Basin portion of the Lyon et al. study (Figure 3-13). Snow cover was not present when the Lyon et al. study was conducted but was very low during this study as well. The most significant meteorological difference between the two studies was temperature.

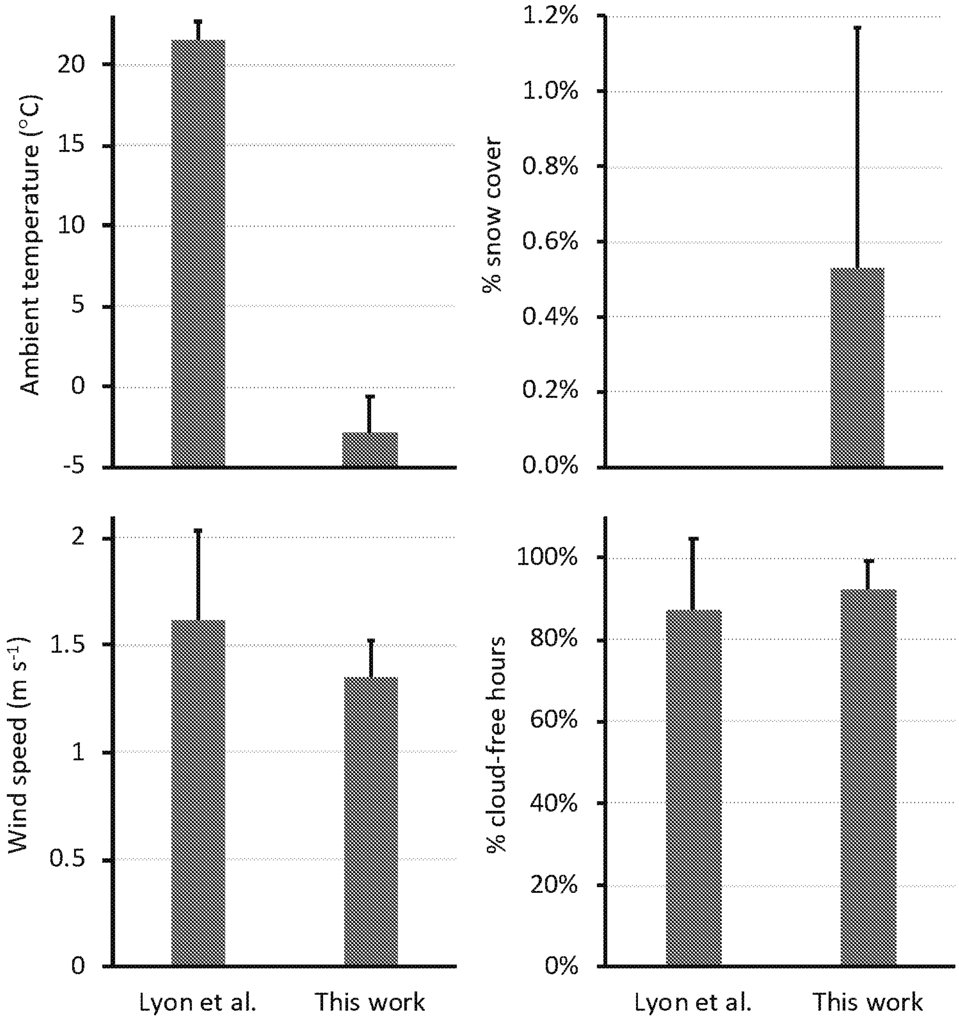

Figure 3-13. Comparison of meteorological conditions during the (Lyon et al., 2016) survey and this study. The panels show (clockwise from top left) ambient temperature, percent snow cover, wind speed, and percent of survey hours that were cloud-free. Top of bars are averages, and whiskers represent 95% confidence intervals.

Lower temperature is associated with poorer detection with infrared leak detection cameras (Ravikumar and Brandt, 2017; Ravikumar et al., 2016), and this could account for much of the difference in detection between the two studies. We used the Ravikumar model of plume detectability by infrared leak detection cameras to explore the extent to which meteorological conditions may have impacted the results of the two studies. For the aerial survey, the background behind the plume was always the ground, so the detection limit was determined by the contrast between the apparent plume temperature (a measure of the amount of infrared energy emitted by and reflected from the plume in the camera's bandwidth of 3.2 to 3.4 μm) and the apparent ground temperature.

Figure 3-14 shows the relationship between the modeled minimum detection limits of the infrared camera and the apparent ground temperature for the meteorological conditions of the two studies. The simulated detection limit was poorest at an apparent ground temperature of about 10°C above the actual ambient temperature. Since the apparent ground temperature was not recorded during the studies, it is impossible to know the actual detection limits with certainty. If we assume the apparent ground temperature was 20 degrees above the ambient air temperature, the methane detection limits for the Lyon et al. study and this study would be about 1 and 4 g s^{-1}, respectively.

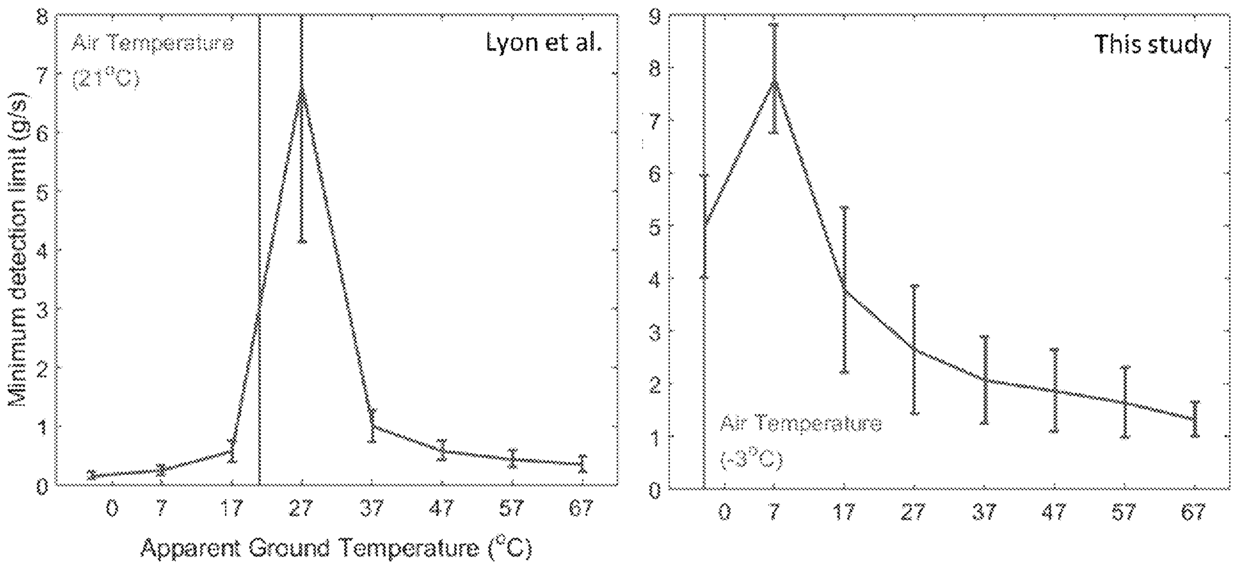

Figure 3-14. Relationship between apparent ground temperature and the minimum detection limit for methane, as calculated using the Ravikumar model. Whiskers represent 95% confidence intervals. The orange vertical lines represent average daytime ambient air temperature.

Controlled hydrocarbon releases provide another way to compare detection limits in the two studies. In this study, the propane plume was marginally detectable somewhere between 1.89 and 5.04 g s^{-1}. Lyon et al. (2016) reported that a methane emission plume of 3 g s^{-1} was marginally detectable. Infrared camera detection limits for propane are about four times lower (i.e., better) than for methane, so we can assume a methane detection limit in our study in the range of 8 to 20 g s^{-1}, between 2.5 and 7 times worse than the detection limits reported by Lyon et al.

Figure 3-15 presents the percent of surveyed well pads with detected emissions, in this work and in Lyon et al., plotted against pad age, the percentage of energy produced at the pad that was from oil, oil production, and gas production. Lyon et al. (2016) plotted these same parameters in their paper in the same way, but for their nationwide dataset, while we only plot Uinta Basin data here. The same general trends can be seen in both studies, with more detected emissions from newer wells, oil wells, and higher-producing wells.

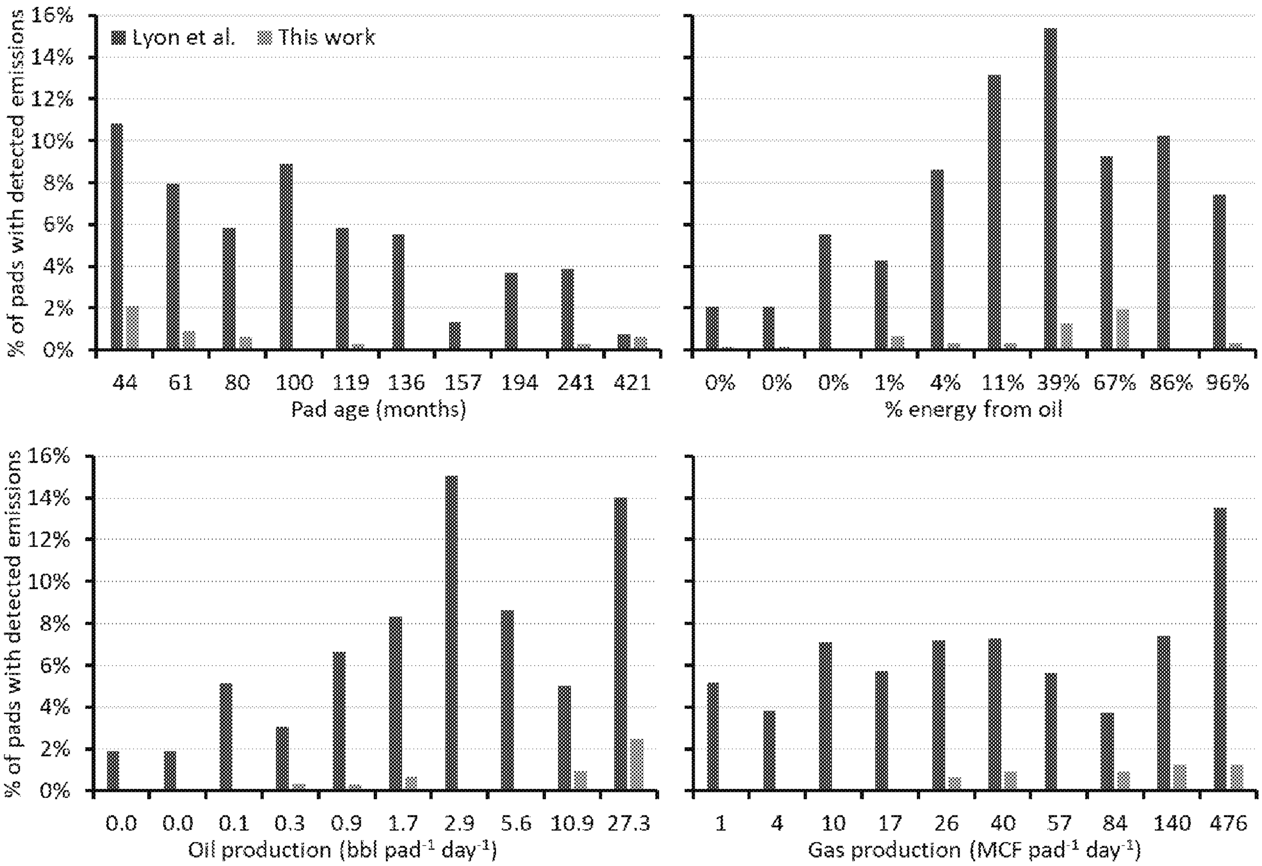

Figure 3-15. Percent of pads with detected emissions versus well properties, in this work and (Lyon et al., 2016). X-axes are organized by decile, and the median of each decile is shown.

3.11. Final Anonymized Dataset

A final anonymized dataset from this study is available at https://usu.box.com/v/2018-USU-IRsurvey.

4. Conclusions

The aerial survey portion of this study detected emissions at a very low percentage of well pads (0.5%) compared to a previous aerial survey (Lyon et al., 2016), at which more than 6% of pads in the Uinta Basin had detectable emissions. Part of the reason for this discrepancy was likely changes in well pad properties (wells in this study were older and lower-producing), but this study also had limits of detection that were between 2.5 and 7 times worse because of cold air temperatures.

The ground survey portion of this study detected emissions at 31% of well pads. Infrared camera emissions detection surveys performed from the ground have much better limits of detection than aerial surveys (at least 10 times better in our controlled propane release study).

Qualitatively small and medium plumes were less likely to be reported as the distance between the camera operator and the well pad increased, and small and medium plumes were never observed at a distance greater than 103 m.

Well pads with detected emissions in the ground and aerial surveys had higher oil and gas production, were younger, and had more liquid storage tanks per pad relative to the entire surveyed population. Oil well pads with higher oil production were more likely to have qualitatively large plumes, while gas well pads with higher gas production were more likely to not have any detectable plumes.

As has been shown in previous studies (Englander et al., 2018; Lyon et al., 2016; Mansfield et al., 2017), the majority of observed emission plumes in this study were from liquid storage tanks (75.9% of all observed plumes), including thief hatches, pressure relief valves, and tank piping.

Well pads with emissions control devices on tanks were more likely to have detected emissions in the ground and aerial surveys, had more detected emissions per pad, and were more likely to have emission plumes that were qualitatively categorized as large. As with the entire population of surveyed well pads, emissions from pads with tank controls originated mostly from tanks (78.1%), as was shown in a previous study (Mansfield et al., 2017). Well pads with tank controls tend to produce higher volumes of oil and gas than wells without tank controls.

Significant differences in the average number of detectable emission plumes per pad, and in the qualitative severity of those plumes, were found among oil and gas companies whose well pads were included in this study. This study is inadequate to ascertain the causes of those differences.

Repairs made by oil and gas companies in response to emissions detected ranged from small maintenance and repair work that cost between zero and a few hundred dollars, to replacement of thief hatches that cost several thousand dollars. Most repairs reported cost well under $1,000.

5. Acknowledgments

This project was funded by the U.S. Bureau of Land Management, the Utah Legislature, the Utah Division of Air Quality, and the U.S. Environmental Protection Agency. It was carried out in cooperation with and under direction from the Ute Indian Tribe and the funding agencies. Personnel employed with these organizations and David Lyon of the Environmental Defense Fund provided helpful comments and assistance in this work. We are grateful to the many oil and gas companies who participated in this project by providing information about the emissions we observed and by providing comments on drafts of this document. We acknowledge the efforts of Colleen Jones, Trevor O'Neil, Randy Anderson (of Utah State University), and Lexie Wilson (of the Utah Division of Air Quality), who completed the fieldwork for the ground survey.

6. References

Brantley HL, Thoma ED, Eisele AP. Assessment of volatile organic compound and hazardous air pollutant emissions from oil and natural gas well pads using mobile remote and on-site direct measurements. Journal of the Air & Waste Management Association 2015; 65: 1072-1082.

CFR. CFR Title 40, Part 60, Subparts OOOO and OOOOa, 2016.

Englander JG, Brandt AR, Conley S, Lyon DR, Jackson RB. Aerial inter-year comparison and quantification of methane emissions persistence in the Bakken formation of North Dakota, USA. Environmental science & technology 2018.

Fox TA, Barchyn T, Hugenholtz C. The winter gap effect in methane leak detection and repair with optical gas imaging cameras. AGU Fall Meeting abstract #A41F-2355, New Orleans, Louisiana, 2017.

Lyon DR, Alvarez RnA, Zavala-Araiza D, Brandt AR, Jackson RB, Hamburg SP. Aerial surveys of elevated hydrocarbon emissions from oil and gas production sites. Environmental science & technology 2016; 50: 4877-4886.

Mansfield ML, Lyman SN, O'Neil T, Anderson R, Jones C, Tran H, et al. Storage Tank Emissions Pilot Project (STEPP): Fugitive Organic Compound Emissions from Liquid Storage Tanks in the Uinta Basin. Utah State University, Vernal, Utah, 2017.

MODIS. MODIS Snow Cover. 2018, 2018.

NCDC. National Climatic Data Center. 2018. National Oceanic and Atmospheric Administration, 2018.

Ravikumar AP, Brandt AR. Designing better methane mitigation policies: the challenge of distributed small sources in the natural gas sector. Environmental Research Letters 2017; 12: 044023.

Ravikumar AP, Wang J, Brandt AR. Are optical gas imaging technologies effective for methane leak detection? Environmental Science & Technology 2016; 51: 718-724.

Ravikumar AP, Wang J, McGuire M, Bell CS, Zimmerle D, Brandt AR. Good versus Good Enough? Empirical tests of methane leak detection sensitivity of a commercial infrared camera. Environmental science & technology 2018.

Subramanian R, Williams LL, Vaughn TL, Zimmerle D, Roscioli JR, Herndon SC, et al. Methane emissions from natural gas compressor stations in the transmission and storage sector: Measurements and comparisons with the EPA greenhouse gas reporting program protocol. Environmental science & technology 2015; 49: 3252-3261.

Thoma ED, Deshmukh P, Logan R, Stovern M, Dresser C, Brantley HL. Assessment of Uinta Basin Oil and Natural Gas Well Pad Pneumatic Controller Emissions. Journal of Environmental Protection 2017; 8: 394.

UDAQ. Uinta Basin: 2014 Air Agencies Oil and Gas Emissions Inventory. 2018, Salt Lake City, Utah, 2018.

UDOGM. http://oilgas.ogm.utah.gov/Data_Center/DataCenter.cfm. 2015. Utah Division of Oil, Gas and Mining, Salt Lake City, Utah, 2018.